Evaluation of a passive arm-support exoskeleton for surgical team members: Results from live surgeries

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Abstract

Background: Musculoskeletal symptoms and injuries adversely impact the health of surgical team members and their performance in the operating room (OR). Though ergonomic risks in surgery are well-recognized, mitigating these risks is especially difficult. In this study, we aimed to assess the impacts of an exoskeleton when used by OR team members during live surgeries.

Methods: A commercial passive arm-support exoskeleton was used. One surgical nurse, one attending surgeon, and five surgical trainees participated. Twenty-seven surgeries were completed, 12 with and 15 without the exoskeleton. Upper-body postures and muscle activation levels were measured during the surgeries using inertial measurement units and electromyography sensors, respectively. Postures, muscle activation levels, and self-report metrics were compared between the baseline and exoskeleton conditions using non-parametric tests.

Results: Using the exoskeleton significantly decreased the percentage of time in demanding postures (>45° shoulder elevation) for the right shoulder by 7% and decreased peak muscle activation of the left trapezius, right deltoid, and right lumbar erector spinae muscles, by 7, 8, and 12%, respectively. No differences were found in perceived effort, and overall scores on usability ranged from “OK” to “excellent”.

Conclusions: Arm-support exoskeletons have the potential to assist OR team members in reducing musculoskeletal pain and fatigue indicators. To further increase usability in the OR, however, better methods are needed to identify the surgical tasks for which an exoskeleton is effective.

Introduction

Work-related musculoskeletal disorders (WMSDs) have remained prevalent among surgical team members, especially during procedures using minimally invasive techniques (Catanzarite et al., 2018; Epstein et al., 2018; Park et al., 2010; Stucky et al., 2018; Tavakkol et al., 2020). The prevalence of WMSDs among surgeons has been reported to be between 73 and 100% during or immediately following conventional laparoscopic surgeries (Catanzarite et al., 2018; Stomberg et al., 2010), and common injuries include rotator cuff pathology among surgeons and interventional medical specialists (Epstein et al., 2018). In addition, WMSDs have been reported among non-surgeon team members, such as bedside technicians and trainees (Athanasiadis et al., 2021). Perioperative nurses and technicians often report low back and shoulder pain (Sheikhzadeh et al., 2009), while surgical residents often report pain in the neck, back, and extremities (Kokosis et al., 2020).

Several interventions have been proposed to address ergonomics deficiencies in the operating room (OR), such as reviewed by Sweeney et al. (2021). To address the biomechanical stresses that accumulate during lengthy procedures, deliberate intraoperative breaks with exercises have had some success in reducing self-reported post-operative pain (Hallbeck et al., 2017; Park et al., 2017). Ergonomic guidelines for positioning OR equipment such as table or monitor height (Miller et al., 2012; Wauben et al., 2006) are another proposed intervention for improving OR ergonomics. Developing and translating new equipment or technology is another common approach proposed to improve surgical ergonomics, and examples include gel-mats (Voss et al., 2017) or introducing robotic technology to enable surgeons to sit while operating (Catchpole et al., 2019). However, interventions that support surgical team members during surgical assisting work – which requires static positioning with irregular need for dynamic motions – are still limited.

A potential intervention that has shown efficacy in supporting the upper-extremity in diverse work tasks is passive exoskeletons (e.g., Kim et al., 2020; McFarland et al., 2022; McFarland & Fischer, 2019; Schwerha et al., 2021, 2022; Upasani et al., 2019). These devices are wearable systems that provide external forces/moments using passive torque generators (e.g., springs or deformable materials, with no electrical components that could have contraindications during surgery). Passive exoskeletons have been demonstrated to improve surgeon and other surgical staff (e.g., nurses) ergonomics, and interest in their applications in other areas of healthcare have been growing (e.g., Hwang et al., 2021; Liu et al., 2018; O'Connor, 2021; Zheng et al., 2022). Specifically, passive exoskeletons have been explored as a potential intervention to address musculoskeletal (MS) risks during patient handling (Hwang et al., 2021; Settembre et al., 2020; Tröster et al., 2020), sonography (Koenig, 2020), and surgery (Bosch et al., 2016; Liu et al., 2018). From pilot tests among surgeons, reduced shoulder pain (Liu et al., 2018) resulted with an arm-support exoskeleton during surgery, and reduced trunk muscle demands were observed during simulated surgical procedures with a back-support exoskeleton (Tetteh et al., 2022). Further, Cha et al. (2020) showed that exoskeletons could be useful for other surgical team members, especially surgical assistants who typically perform static holding of surgical instruments and tools (e.g., holding a laparoscopic camera or retractors for surgical field visualization).

While exoskeletons appear to have potential for improving ergonomics in work that is static or requires non-neutral positions in other domains, we are unaware of studies that have objectively assessed the use and compared the effectiveness of arm-support exoskeletons for various surgical team members (e.g., surgeons, trainees, and surgical technicians) during live surgery. Thus, the objective of this work was to conduct a pilot study with a passive arm-support exoskeleton among several surgical team members in the OR, during live surgical procedures. Body postures and muscle activity, along with subjective perceptions, were measured during surgeries conducted both with and without the exoskeleton. The responses were used to evaluate the potential for exoskeletons to reduce MS risks among various surgical team members.

Methods

Study Participants

Institutional Review Board approval was obtained for this study. Participants were recruited from among surgical team members at a large Midwest hospital via convenience sampling and word of mouth.

Exclusion criterion included individuals with self-reported current or recent (past 12-month) MS problems or injuries that prevent normal daily activities. Surgical team members included attending surgeons, surgical technicians/assistants, and surgical trainees (e.g., fellows, residents, and medical students during their surgical rotation). Informed consent was obtained from the participating surgical team member, the patient, and the attending surgeon of a procedure.

Data Collection

A light-weight (3.2 kg) arm-support exoskeleton was used for this study (Levitate AIRFRAME™; Figure 1), which was selected since the device was developed initially for use during surgery and had a minimal profile (i.e., more easily donned under sterile surgical gowns). A research team member trained by the exoskeleton manufacturer helped participants don the device, by fastening a waist strap and positioning arm cuffs above the elbow. In the study, one of the two lower levels of support were used, by having participants self-select the appropriate cartridge (level 1 or 2). Throughout the surgical procedures, motion tracking and wireless surface EMG (sEMG) sensors were used to obtain body postures and muscle activity, respectively. Participants wore five inertial measurement units (IMUs; 128 Hz, SXT2, NexGen Ergonomics), which were placed on the forehead, sternum, trunk, and left/right bicep. Six sEMG sensors (2000 Hz, DataLITE wireless EMG sensors, Biometrics Ltd, UK,) were placed bilaterally over three muscle groups: anterior deltoids, descending trapezius, and lumbar (L4) erector spinae.

Subjective responses were obtained using a questionnaire, adapted from an existing body-part discomfort survey (Huang, 1999) to indicate participants' overall level of perceived physical *discomfort* and localized discomfort at 25 distinct body regions. For each, a 10-point rating scale was used (0 = no discomfort, 10 = maximum discomfort). For upper-body areas (e.g., head/neck and arms) and the back, perceived *effort* was also reported on 10-point scales (0 = no perceived effort, 10 = perceived effort). To assess the usability of the exoskeleton, the System Usability Scale (SUS) was completed (Brooke, 1996).

Figure 1. Participant wearing the exoskeleton before surgery (left), a demonstration of how arms can be supported (middle), and a participant wearing the exoskeleton under a sterile gown during surgery (right).

Data were collected during 27 procedures, 15 baseline (no exoskeleton) and 12 with the exoskeleton. Seven participants were involved: one surgical technician (7 procedures), five surgical trainees (18 procedures), and one attending surgeon (2 procedures). All procedures were laparoscopic or open procedures within general or bariatric surgery. Four of the seven participants were female, all were right-hand dominant, and mean (SD) stature and body mass were 167 (13) cm and 68 (10) kg. Procedure durations had a mean (SD) of 111.6 (62.4) minutes; an unpaired *t* test indicate no significant difference between durations between baseline and exoskeleton conditions ($p = 0.61$).

Study Procedures

Baseline measurements and measurements with the exoskeleton were collected during separate procedures, and the order of the baseline and exoskeleton conditions was randomized. The exoskeleton was fitted by a study team member who was certified by the exoskeleton manufacturer. During the donning period, participants selected a preferred level of arm support (between levels 1 and 3). The exoskeleton was worn under the sterile surgical gown (Figure 1).

IMU sensors were calibrated prior to the beginning of a procedure, using a modified I-pose, specifically the standard I-pose, but with elbows flexed 90° to avoid contaminating sterility (Asadi et al., 2021; Athanasiadis et al., 2021). For EMG normalization, two maximum voluntary contractions (MVCs) were completed for 10 seconds each. For the upper body muscles, participants adopted 45° of shoulder abduction and exerted maximum isometric force against a static resistance provided by study team members (Athanasiadis et al., 2021). For the trunk muscles, participants were prone on the ground and performed a maximum isometric back extension effort against resistance provided by a study team member (Jackson et al., 2017). Although these postures may not represent the optimal length for the measured muscles, these postures were selected due to time constraints in the operating room and were used only for the purpose of normalization. Prior to and at the completion of each procedure, participants reported their perceived discomfort and perceived effort in upper-body areas (e.g., neck, back, left/right arm). The SUS survey was completed only after procedures done with the exoskeleton to assess usability.

Data Analysis

Drawing from previous studies involving ergonomic metrics (Asadi et al., 2021; Athanasiadis et al., 2021; Yu et al., 2017), several outcome measures were calculated. These metrics were calculated across the entire duration of a given procedure. Data from the IMUs were transformed from quaternions into posture angles using custom MATLAB (MathWorks, Natick, MA, USA) scripts (Yu et al., 2017). Transformation matrixes that utilized the relationship between the quaternions and Euler angles were applied to convert the quaternions outputs into Euler angles (Henderson, 1977). These Euler angles represented body-segment rotations, and posture angles were calculated using definitions from the International Society of Biomechanics (Wu et al., 2002, 2005). Following earlier reports, static postures were defined and calculated as the percentage of time during which joint angular velocity was < 1°/s (Szeto et al., 2012; Yu et al., 2017). Time in demanding postures was also obtained, and such postures were defined when angles were outside the range of recommended limits of the Rapid Upper Limb Assessment (RULA): >10° neck flexion, >20° trunk flexion, and >45° shoulder elevation (McAtamney & Corlett, 1993). EMG data were analyzed using MATLAB to derive percentile (%ile) values as percent MVC, with 10th%ile representing static demands, 50th%ile representing dynamic demands, and 90th%ile representing peak load (Jonsson, 1982; Veiersted et al., 2013). To detect localized muscle fatigue, power spectrum analyses were performed using Fast Fourier Transforms, from which median power frequency (MdPF) was calculated using 125 msec windows with 62.5 msec overlaps (McDonald et al., 2019). As is commonly done, a decrease in MdPF was interpreted as reflecting localized muscle fatigue (De Luca, 1997; Merletti et al., 1991).

All metrics were compared between the exoskeleton and baseline conditions using non-parametric, unpaired Wilcoxon Rank Sum tests in R (©R Studio, v1.1.456), with α = 0.05. We experienced initial challenges in integrating the sensors with the participants' work requirements, such as securing trunk EMG sensors accounting for perspiration under the surgical gown or IMU sensors moving due to the exoskeleton arm support. As a result, some sensor data were excluded due to poor quality: five procedures for back EMG, three procedures for left deltoid EMGs (one of which was same as the back EMG), and one procedure for IMUs. Survey responses from 22 procedures were obtained for the overall discomfort survey; five were missing due to surgical workflow constraints (i.e., insufficient time between procedures to complete surveys).

Results

Table 1 summarizes the posture angles measures and the statistical results. Using the exoskeleton led to a significant decrease (from 11.0 to 3.8 %) in the percent time in demanding postures for the right shoulder. No other significant differences were found between procedures with and without the exoskeleton for any other posture metrics. The exoskeleton also caused a decrease in the percent time in demanding postures the left shoulder (from 22 to 5 %), although this difference was not significant.

Table 1. Summary of posture angle metrics and results from comparisons between conditions.

Posture angle	Metric	Condition				Baseline v. Exoskeleton Conditions	
		Baseline		Exoskeleton		Wilcoxon *W*	*p*-value
		Mean (SD)	Range	Mean (SD)	Range		
Trunk	Mean (°)	4.49 (10.28)	-13.66 - 16.75	8.76 (15.33)	-13.48 - 31.87	23	0.61
	%Time in Static	81.95 (10.84)	65.99 - 92.94	77.15 (18.91)	41.23 - 96.46	29	0.96

	%Time in Demanding	10.31 (10.64)	0 - 28.51	24.48 (31.74)	0 - 90.98	23	0.56
Neck	Mean (°)	6.79 (13.31)	-7.67 - 23.45	5.14 (12.63)	-8.94 - 19.52	19	0.88
	%Time in Static	67.17 (16.88)	43.68 - 90.34	53.1 (24.79)	28.31 - 97.38	28	0.37
	%Time in Demanding	38.23 (32.51)	2.36 - 81.77	59.22 (33.11)	14.01 - 92.31	13	0.30
Left Shoulder	Mean (°)	31.59 (17.47)	11.05 - 60.32	23.75 (10.12)	7.77 - 38.84	36	0.40
	%Time in Static	72.78 (16.28)	46.08 - 88.31	73.26 (19.13)	43.68 - 96.49	28	1.00
	%Time in Demanding	21.78 (24.21)	0.29 - 68.74	4.94 (7.57)	0 - 21.7	40	0.19
Right Shoulder	Mean (°)	24.39 (11.63)	11.85 - 51.31	23.57 (9.2)	14.1 - 37.46	28	1.00
	%Time in Static	74.77 (14.3)	50.9 - 91.14	71.62 (19.06)	40.49 - 97.22	29	0.96
	%Time in Demanding	11.01 (12.55)	2.59 - 41.05	3.8 (4.55)	0.82 - 13.84	47	**0.03**

Bold *p*-value indicates a significant difference between conditions. Neck and trunk angles are on the sagittal plane, and negative angles represent extension. Shoulder angles are indicative of shoulder elevation relative to the calibration I-pose.

Table 2 summarizes the results for metrics of muscle activation. Using the exoskeleton decreased right deltoid 90th%ile activation (from 15.4 to 7.5 %MVC). For the left trapezius, the exoskeleton caused decreases in 10th%ile activation (from 1.0 to 0.6 %MVC), 50th%ile activation (from 2.0 to 1.4 %MVC), and 90th%ile activation (from 11.6 to 4.7 %MVC), and an increase in MdPF (from 64.3 to 77.0 Hz). For the right erector spinae with the exoskeleton, 50th%ile activation decreased (from 7.7 to 3.5 %MVC), as did 90th%ile activation (from 21.0 to 9.4 %MVC). No significant effect of exoskeleton use was found in the activations of the right trapezius, left deltoid, or left erector spinae. Other changes with exoskeleton use were notable, though not statistically significant: a decrease in 90th%ile activation for the left deltoid and right trapezius, a decrease in MdPF of the right deltoid and left erector spinae, and a decrease in 10th%ile activation of the right erector spinae. Comparison of the significant metrics per subject is included in the Appendix.

Table 2. Summary of muscle activation metrics.

Muscle	Metric	Condition				Baseline v. Exoskeleton Conditions	
		Baseline		Exoskeleton		Wilcoxon *W*	*p*-value
		Mean (SD)	Range	Mean (SD)	Range		
Left Deltoid	10%ile %MVC	0.72 (0.48)	0.28 - 2.05	0.84 (0.93)	0.29 - 3.37	71	0.98
	50%ile %MVC	1.72 (1.58)	0.53 - 6.45	1.92 (2.76)	0.45 - 9.5	81	0.55
	90%ile %MVC	7.85 (5.12)	2.44 - 18.05	6.24 (6.75)	1.04 - 21.93	97	0.12
	MdPF	59.91 (14.01)	38.18 - 95.78	57.21 (12.78)	43.39 - 88.77	106	0.46
Right Deltoid	10%ile %MVC	1.46 (1.73)	0.51 - 7.53	1.17 (1.37)	0.41 - 5.18	106	0.24
	50%ile %MVC	3.44 (4.6)	0.86 - 19.28	2.32 (2.41)	0.74 - 8.94	102	0.33
	90%ile %MVC	15.38 (9.37)	2.23 - 37.19	7.47 (5.67)	1.73 - 20.12	127	**0.02**
	MdPF	78.14 (22.73)	41.75 - 102.49	61.24 (29.75)	27.98 - 97.04	120	0.15
Left Trapezius	10%ile %MVC	1 (0.44)	0.63 - 2.42	0.66 (0.42)	0.2 - 1.69	129	**0.02**
	50%ile %MVC	2.3 (1.61)	1.27 - 7.63	1.43 (1.23)	0.33 - 4.75	127	**0.02**
	90%ile %MVC	11.56 (5.14)	4.62 - 21.3	4.71 (3.07)	1.15 - 10.97	147	**<0.01**
	MdPF	64.27 (16.5)	26.96 - 79.71	76.95 (19.51)	33.57 - 105.33	44	**0.02**
Right Trapezius	10%ile %MVC	1.22 (0.7)	0.68 - 3.17	1.88 (3.1)	0.16 - 10.87	102	0.33
	50%ile %MVC	2.86 (2.18)	1.12 - 8.08	3.6 (5.34)	0.27 - 18.77	97	0.47
	90%ile %MVC	13.82 (6.97)	4.62 - 26.2	13.03 (17.22)	1.03 - 50.5	112	0.13
	Median Power Frequency	80.82 (14.15)	41.64 - 101.93	81.6 (14.69)	52.05 - 105.09	84	0.79
Left Lumbar Erector Spinae	10%ile %MVC	5.1 (4.15)	1.4 - 13.5	3.58 (3.17)	0.22 - 10.81	71	0.43
	50%ile %MVC	11.85 (6.21)	3.64 - 22.71	8.84 (7.22)	0.38 - 20.27	74	0.32
	90%ile %MVC	32.16 (19.03)	11.78 - 65.82	29.64 (29.85)	1.17 - 94.1	70	0.47
	MdPF	91 (29.92)	46.81 - 120.55	69.08 (26.52)	39.39 - 106.37	81	0.10
Right Lumbar Erector Spinae	10%ile %MVC	4.06 (3.73)	1.29 - 11.41	1.44 (0.72)	0.45 - 2.46	42	0.11
	50%ile %MVC	7.69 (4.29)	2.7 - 15.85	3.47 (1.91)	0.77 - 5.38	47	**0.03**
	90%ile %MVC	21 (13.18)	10.14 - 50.3	9.35 (5.33)	2.33 - 15.7	46	**0.04**
	MdPF	79.66 (28.12)	41.5 - 120.7	82.26 (18.09)	53.67 - 104.42	46	0.86

Bold *p*-values indicate significant difference between conditions.

Mean (SD) increases of overall discomfort from before to after procedures were 0.3 (0.9) and 0.4 (1.0) for the baseline and exoskeleton conditions, respectively, though this difference was not significant (*p* = 0.88). Changes for each body region are summarized in Table 3. Although decreases of perceived effort with exoskeleton use were evident, none of the effects of exoskeleton use were significant (Figure 2). SUS scores had a mean (SD) of 74.7 (3.2), with a range from 70 to 80 (max = 100).

Table 3. Change in perceived discomfort at several body region (after - before procedure) in both the baseline and exoskeleton conditions.

Body Region	Condition		Baseline v. Exoskeleton Conditions	
	Baseline Mean (SD)	Exoskeleton Mean (SD)	Wilcoxon *W*	*p*-value
Head	0.0 (0.0)	-0.1 (0.3)	65	0.27
Neck	0.1 (0.6)	0.0 (0.0)	59	1.00
Upper Back	0.5 (1.4)	0.0 (0.0)	68	0.26
Left Shoulder	0.1 (1.7)	0.1 (0.8)	54	0.72
Right Shoulder	0.0 (1.4)	0.1 (0.8)	51	0.52
Left Upper Arm	0.1 (1.0)	0.2 (1.2)	54	0.68
Right Upper Arm	0.2 (1.1)	0.3 (1.0)	56	0.86
Left Elbow	0.0 (0.0)	0.0 (0.0)	59	n/a
Right Elbow	0.0 (0.0)	0.0 (0.0)	59	n/a
Left Lower Arm	0.0 (0.0)	0.0 (0.0)	59	n/a
Right Lower Arm	0.0 (0.0)	0.0 (0.0)	59	n/a
Left Wrist/Palm	0.0 (0.0)	-0.1 (0.3)	65	0.27
Right Wrist/Palm	0.1 (0.3)	0.0 (0.0)	63	0.46
Left Fingers	0.0 (0.0)	0.1 (0.3)	52	0.27
Right Fingers	0.0 (0.0)	0.1 (0.3)	52	0.46
Lower Back	0.2 (1.3)	0.7 (1.3)	50	0.47
Buttock	0.1 (0.3)	0.0 (0.0)	63	0.46
Left Thigh	0.1 (0.3)	0.0 (0.0)	63	0.46
Right Thigh	0.2 (0.6)	0.0 (0.0)	63	0.46
Left Knee	0.0 (0.0)	0.0 (0.0)	59	n/a
Right Knee	0.0 (0.0)	0.0 (0.0)	59	n/a
Left Leg	0.3 (1.4)	-0.1 (0.3)	65	0.89
Right Leg	0.4 (1.4)	0.0 (0.0)	63	0.46
Left Ankle/Foot	-0.2 (0.6)	-0.1 (0.3)	60	0.27
Right Ankle/Foot	0.1 (1.3)	0.0 (0.0)	63	0.65

p-value n/a due to no differences between conditions.

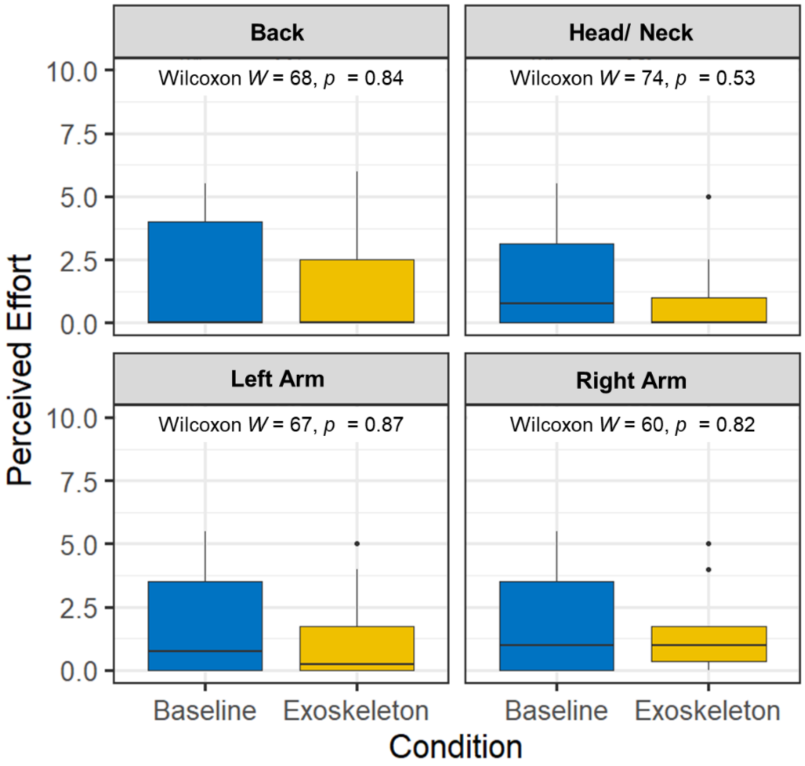

Figure 2. Perceived effort at four body regions in the baseline (*n* = 13) and exoskeleton (*n* = 9) conditions.

Discussion

MS symptoms, fatigue, and injuries have an important impact on worker health and performance in surgical environments (Athanasiadis et al., 2021; Dalager et al., 2020). Surgical team members often experience MS symptoms that include discomfort or pain during and after surgery (Cha et al., 2020). In this study, we investigated the use of an arm-support exoskeleton as an intervention during surgery to reduce MS symptoms and fatigue. This pilot implementation of an exoskeleton provided preliminary evidence that passive arm-support exoskeleton technology has the potential to alleviate physical demands among surgical team members and reduce indicators of MS symptoms.

Use of the exoskeleton did not significantly change the participants' postures angles and time in static postures, which suggests that the technology did not interfere with the surgical work tasks. Moreover, the decrease of time in demanding shoulders postures indicates that the exoskeleton led to participants remaining closer to neutral, non-elevated shoulder orientations. This change could be due to the exoskeleton shoulder straps restricting movement and rounding of the shoulders, which then caused participants to increase trunk flexion to be closer to the patient/surgical field (note that there was a non-significant increase in mean trunk flexion with the exoskeleton).

Decreases in muscle activation metrics were observed with the exoskeleton. The decreases in peak (90th%ile) muscle activation of the right deltoid, left trapezius, and right erector spinae suggest that the exoskeleton provided support to the participants' shoulders during the operations. These finding agree with a previous study that reported a reduction in shoulder muscle activity during simulated surgical tasks when using the same arm-support exoskeleton used here (Tetteh et al., 2022). Moreover, although the exoskeleton shifts the upper extremity load to other body regions, there was no indication of increased effort in the back when using the device among the participants. In addition, there was a lower MdPF in the baseline condition, suggesting more fatigue than when using the exoskeleton (De Luca, 1997; Merletti et al., 1991). This reduction in fatigue could be due to the changes in postures with the exoskeleton. The general decrease in muscle activation metrics with the exoskeleton, with the consistency of posture angles while using and not using the technology, are promising indicators that the exoskeleton reduces muscle activation of users during surgery.

In contrast, increased signs of muscle fatigue were observed when using the exoskeleton for the right deltoid (i.e., decrease MdPF). Surgical trainee participants noted that the added resistance during fine motor control tasks such as suturing were more difficult with the exoskeleton, due to increased effort to position the arms. This resistance may have been particularly noticeable since all participants were right-hand dominant and often completed tasks with their dominant arm. Signs of fatigue could also be indicative of the task demand effects on the right deltoid, regardless of wearing an exoskeleton. Moreover, although the exoskeleton could cause compensatory responses in other body regions, there was no indication of increased effort in the back when using the device among the participants during surgery, which agrees with results from other studies (Desbrosses et al., 2021; Ojelade et al., 2023).

From the survey responses, participants did not note significantly more discomfort or perceived effort while completing procedures while wearing the exoskeleton. Most participants also noted that the device was not distracting and did not require more effort than performing the procedure with the exoskeleton. Moreover, participants reported that trunk postures remained closer to neutral due to the rigid structure of the device, which in turn may have led to increased neck extension to accommodate their positioning for proper visualization for the OR monitors. Several participants also stated feeling increased resistance on the arms and difficulty in turning their wrists due to the cuffs pushing against their arms, especially during suturing. One participant noted readjusting their arms for better positioning and support, due to feeling that their arm was not centered on the arm cuff. However, from the usability survey responses, the exoskeleton was considered usable and within the “OK” to “Excellent” ranges (Bangor et al., 2009). This acceptable range of usability following use *in situ* shows the potential for the exoskeleton use to provide upper body support to surgical team members in the OR.

Among the surgical roles included this work, arm-support exoskeletons may be most beneficial for and least hinder the work tasks of the surgical technicians. Attending surgeons and surgical trainees who complete fine motor tasks indicated that the device may be more helpful for tasks not requiring fine movements. The surgical technician, who typically does not have to complete fine motors tasks, did not echo this concern, suggesting that the technology may benefit individuals who are assisting the surgical team during tasks such as holding the endoscope (Cha et al., 2020).

When comparing our findings from live surgeries to studies in live or simulated surgeries, similar objective and subjective findings were found. Tetteh et al. (2022) reported reduced medial deltoid muscle activity during simulated vascular surgery tasks, which complements our findings. Overall decreases in perceived discomfort/pain were found in this and the work of Liu et al. (2018); specifically, both studies reported decreases in discomfort in the shoulders and upper arms when using the exoskeleton. In addition, exoskeleton usability scores were lower in live vs. simulated scenarios (Cha et al., 2020), although these scores remained in a positive range in the former. Thus, while findings from simulation studies may not fully represent the challenges of live surgeries, the consistency in overall findings suggests that arm-support exoskeletons can be a tool for surgical staff to reduce musculoskeletal pains and injuries (Li et al., 2023).

Future work is needed to expand on these preliminary results. From our initial observations, the types of procedures included may not be the optimal procedures to benefit from arm support. Authors of a previous study noted that the use of exoskeletons in specialties with longer procedure durations (e.g., greater than three hours) may be the most effective (Cha et al., 2020). Specialties with different distributions of task demands, such as ear, nose, and throat procedures, or those needed in microsurgery (Yu et al., 2014, 2016), may include different task demands in which the exoskeleton could support the long static postures typically required. Additional physiological indicators, such as energy expenditure and EMG from other back muscles (e.g., longissimus), could be obtained to better understand the effects of exoskeletons on users (Ivaldi et al., 2021; Maurice et al., 2019). Furthermore, although the baseline and exoskeleton procedures here were in the same specialty, further work should investigate specific task demands for different surgical roles during the procedure. For example, such could parse outcome metrics for each surgical step and characterize the duration in specific postures, Doing so would facilitate direct comparisons of biomechanical indicators with vs. without the technology and identify if exoskeleton support may be more beneficial for particular surgical steps and associated postures. (Athanasiadis et al., 2021; Meltzer et al., 2020; Yu et al., 2017). Doing so will build on the limited reported of longitudinal studies and help in understanding cumulative effects of exoskeletons (Kim et al., 2021). Finally, exoskeleton design aspects should be further explored to understand individual considerations of users for proper fit and appropriate assistance level to complete intraoperative tasks, especially considering the diversity of gender and age (McFarland et al., 2022). Further evaluation on different exoskeleton designs (e.g., back-support instead of arm-support) are also warranted.

In conclusion, arm-support passive exoskeleton technology has the potential to be an effective wearable intervention to reduce MS symptoms among surgical team members. With increased sample size with diversity of team member roles and types of procedures, the generalizability of the results will be increased. If evidence of the reduction of MS symptoms from the use of exoskeletons are found, training and education strategies should be developed to facilitate integration for safe and effective adoption.

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Conflict of Interest/Disclosure

The authors have no conflict of interest to report.

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Appendix

Figure A1: Subject-specific responses with and without exoskeleton regarding the time in demanding postures of the right shoulder. Comparisons were not possible for three subjects due to missing data.

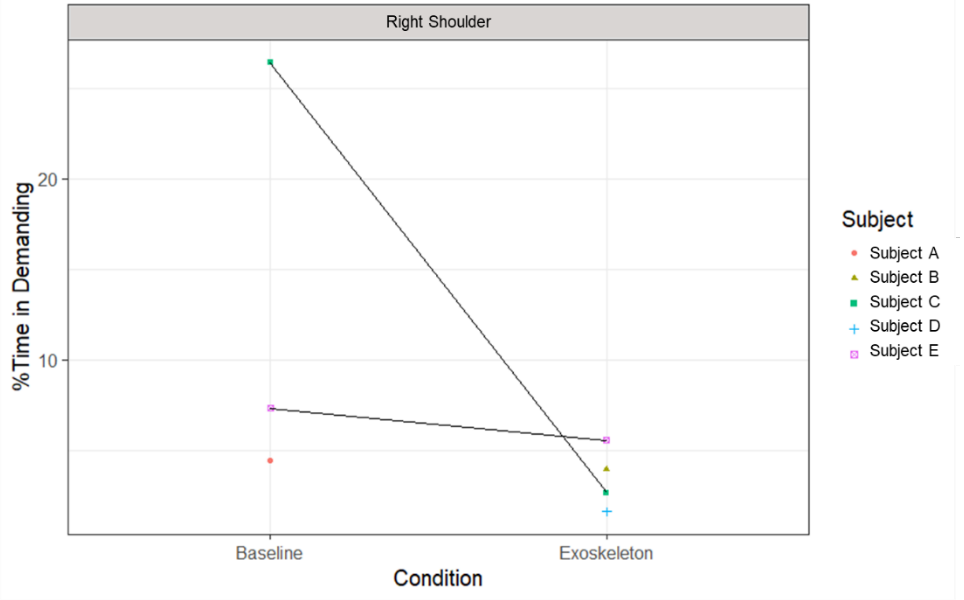


Figure A2: Subject-specific responses with and without exoskeleton regarding muscle activity metrics of left trapezius. Comparisons were not possible for one subject due to missing data.

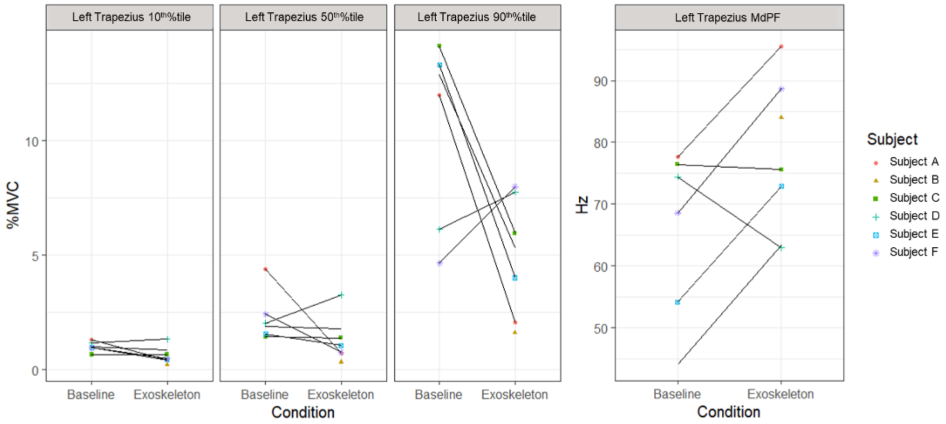
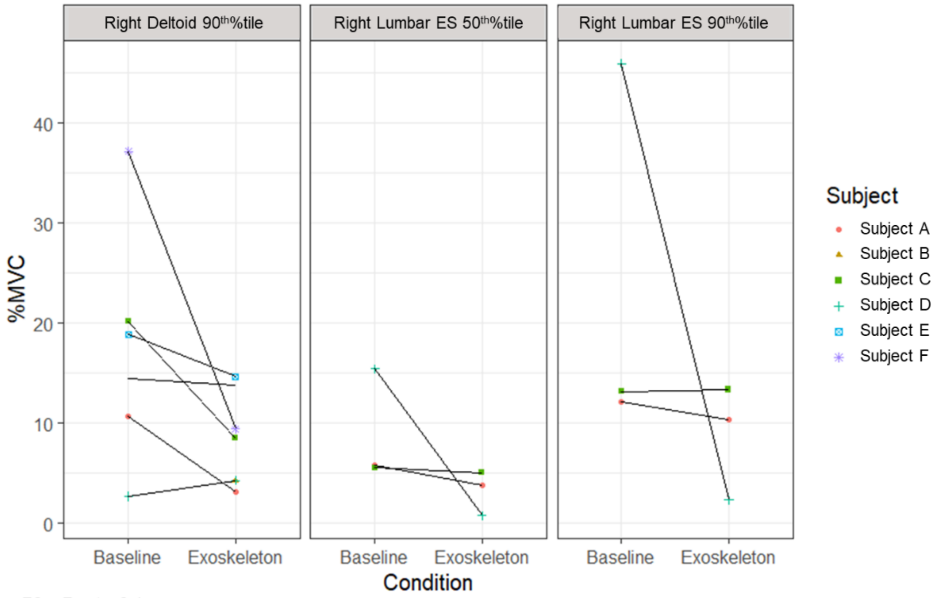


Figure A3: Subject-specific responses with and without exoskeleton regarding muscle activity metrics of 90th%tile right deltoid and 50th%tile and 90th%tile right lumbar erector spinae. Comparisons were not possible for one subject for the right deltoid and four participants for the right erector spinae due to missing data.



ES = Erector Spinae